SYNOPSIS

The compatibility of shallow foundation on the soil can be improved by one of the techniques known as skirted foundation where the skirts are built-in with the footing which become effective in improving foundation-soil interaction by confining sand within the skirts due to improved state of stress. To understand the behaviour of skirted footing, it is necessary first to understand the behaviour of conventional plane footing.

CONVENTIONAL PLANE FOOTING

The Terzaghi's theory of bearing capacity of shallow foundation is based on several assumptions of ideal behaviour of the foundation on soil media. The experimental observations reflect the deviation from a few factors such as size effects of foundation, compressibility, and failure criterion of the media over which the foundation is supported. However, the basic concept which Terzaghi put forth was adopted in practice accounting for various factors dealing with the different load conditions such as axial, eccentric, and oblique loads, and for contact pressure distribution of soil below the foundation.

Vesic et al. (1969), studied the scale and compressibility effect on bearing capacity factors and mentioned that the value of $N_u$ for arbitrary large footing may be much smaller than conventionally assumed. The bearing capacity of the soil is related with the compressibility of soil and size of footing taking into account the void ratio at failure, incorporating the 'rigidity factor' by employing the solution for cavity expansion in elasto-plastic soils.

Although, the post-Terzaghi applications to bearing capacity of soil under shallow foundations were limited to axisymmetrical plane strain case, a group of research workers consisting of Mayerhof (1951, 53), Terzaghi and Peck (1967), Berezantsev (1952), Sokolovski (1960), Cox (1962), Vesic (1973), De Beer (1970), etc. worked on static and transient loading on footings. Main expositions of the above workers seem to be in some sense quantitative in nature rendering too remote from rational method for dilatant granular mass. Further, these research workers remained confined to modify the base angle and shape of the spiral and the equation of failure line considering the mode of failure by suitable modification in frictional parameter of soil and verification by experimental model footings in laboratory.

Before proposing the theoretical development for skirted strip footing, the present work has attempted to modify the Terzaghi’s theory for conventional plane footing considering the following points:

1. The frictional parameter under the footing in zone I, is modified to $\phi_m$ taking into account the scale effect. The theoretical relation for modification in $\phi$ is $\tan \phi_m = \{\exp (C_s \tan \phi)\} \tan \phi$, where $\exp (C_s \tan \phi)$ represents the coefficient due to scale effect. The factor $C_s$ is given by an empirical relation $C_s = 0.15 - 0.4 \sqrt{B}$, $B$ being the footing width in metres.

2. The equation of the radius $r$ of the log spiral making an angle $\theta$ with the base radius $r_0$, is modified to $r = r_0 \exp (\theta \tan \phi)$ incorporating the variation in friction parameter where $\phi_1 = \phi_m$ at zone I varying linearly to $\phi_1 = \phi$ at zone III along the failure line. The variation of $\phi$ in radial shear zone seems to be optimistic approach reflecting the variation in $\phi$ due to scale effect.

3. The variation in the locus of the centre of log spiral is considered to obtain the minimum possible value of $N_q$ unlike Terzaghi’s fixed centre of log spiral at the edge. For getting minimum value of $N_t$, the variation in the locus of log spiral is considered similar to that of Terzaghi.

A computer programme is developed for the computations of bearing capacity factors $N_q$ and $N_t$ by considering all these points. To satisfy the needs of relative compressibility, the lower limiting values are justified in assigning to $c'$ and $\phi'$ where $c' = (2/3) c$ and $\tan \phi' = (2/3) \tan \phi$, which also conforms stress - strain relation of the material (Terzaghi-1943). For mixed mode failure, the gradual transition as advocated by Peck, Hansen, and Thournborn (1957) can be the appropriate method. To avoid cumbersome concept of expansion of cavity as suggested by Vesic to account of relative compressibility, the present work has continued to adopt the Terzaghi’s approach of accounting relative compressibility.
SKIRTED STRIP FOOTING:

A group of research workers including Rao and Narahari (1979), Borthakar et al. (1992), Gopal Ranjan et al. (1983,91) and A. N. Patel et. al. (1992) attempted in developing skirted plug and ring foundation. Rao and Bhandari (1980) used skirted footing heavy storage tank foundation. In all these cases the skirts were not built-in with footing but located at farther distance. Hanna et al. (1989) developed triangular shell strip footing. Kurian N. P. (1982), Alam Singh et al (1987), Chawdhary (1987), used model skirted footing with built-in skirts and noted the improvement in load carrying capacity. Principle objectives of these workers have been confined to study the increased load carrying capacity without explaining the appropriate mechanism of the state of stress within the skirt alongwith the contact pressure distribution below the skirted foundation and pressure distribution in the soil mass.

THEORETICAL DEVELOPMENT

Shroff and Shah (1996) proposed a theoretical model for computing the bearing capacity factors \( N_{qs} \) and \( N_{ma} \) for a skirted strip footing based on classical mathematical scheme of Terzaghi from a mechanism of densification of grains due to skirts and its effect on elasto-plastic equilibrium of granular mass considering the compatibility conditions of footings with sand mass.

The present work has proposed a mathematical relationship for frictional parameter based on inherent dilatant properties of sand taking in to account the state of stress of sand mass within the skirts which are built in with the footing. Proposed mechanistic model of confined sand mass exhibits increase in its modulus of elasticity \( E \) that is verified by FEM analysis employing the ANSYS software and also by in-situ density measurement of sand in testing set up. This modified friction parameter is used for evolving the bearing capacity factors. These factors found by developing computer programme. The relation proposed for modified friction parameter under the footing is \( \tan \phi_m = (\exp(C_s \tan \phi + C_i)) \tan \phi \). The scale effect is incorporated by the factor \( C_s = 0.15 - 0.4 \sqrt{B_1} \), where \( B_1 \) is the projected width of the footing. The improved state of stress within the skits is included by the factor, \( C_i = ((A_1/A_2)^{0.8} - 1) (e - e_{min})^{0.5} \), where \( A_1 \) and \( A_2 \) are the areas of inert triangular wedge under skirted strip footing, and conventional footing having the same interacted contact area of footing with sand respectively, and \( e \) and \( e_{min} \) are the initial and minimum void ratio at the densest state respectively.
The above mathematical model is extended for eccentric, oblique and horizontal loads. For eccentric loads the rupture surface is assumed on the side of the loads. The passive resistance is fully mobilised on the failure side and partial on the other. The failure side of the footing subjected to oblique loads is dependent on the incident load line on the bottom plane surface of the skirted footing with respect to its center-line. For horizontal loads the failure loads are determined by considering the modified angle of friction within the skirts and passive resistance of soil against outer surface of the skirt.

The theoretical curves for bearing capacity factors \( (N_q, N_{qs}, N_t, \text{and } N_{pa}) \) for various sizes of conventional and skirted strip footings are plotted for axial, eccentric, and oblique loads. Above factors are plotted for different values of angle of internal friction of sand for conventional footings.

**EXPERIMENTAL MEASUREMENTS**

The scheme to verify the proposed mechanistic model is to conduct a series of tests so as to prove its efficacy against the physical factors namely width, skirt angle and width of skirt on conventional and strip footing models subjected to the axial, eccentric, oblique and horizontal loads. Prior to planing the actual experimental programme preliminary experiments were carried out in order to design the thickness and base roughness of experimental models/prototype footings. The edges of footings are made vertical so as to minimise the errors of calculation.

A series of load test on conventional and skirted strip model footing are conducted for above factors in load test set up comprising of mild steel tank with dimension 200mm X 820mm X 500mm for small models, and 1.2m x 1.2m x 1.2m and 1.2m X 1.8m X1.2m deep for medium models. The uniform vertical and eccentric strip loads were made effective through an L-section from 50 kN capacity screw jack and load cell. A wedge shaped teak wood block is used to distribute the load uniformly throughout length at center and at required eccentricity \( e_x \) in \( x \) direction. A system comprising of pulley along with a sensitive spring located nearer to the model is used to apply the correct horizontal load. A system consisting of pressure cells and load cells interfaced with indicators along with extensometer is deployed to measure the displacement and vertical soil pressure below the footing in the foundation sand mass, the contact pressure measurement directly below the skirted footing, and load-displacement measurements. The dentoplast material is used for housing the pressure cells in the models for contact pressure measurement.
For prototype testing a large size foundation testing set up is designed and developed having a testing pit of 3m x 5m x 4.5m dimensions. The load is made effective through a stiff reaction beam anchored at column supports. To maintain the equilibrium in this set up, the columns are supported through a number of anchor piles.

About 50 models of different dimensions using mild steel are fabricated to fulfil the requirement of the testing programme. About 150 experiments are planned and performed to examine the several factors mentioned earlier. Large size prototype models are fabricated and tested to observe the performance of the skirted footing in the field.

SUMMARY OF FINDINGS

The experimental data from a verity of tests performed during this investigation are analysed and discussed from fundamental considerations. Non-dimensional parameters used to analyse the results are “Bearing Capacity ratio” (BCR), “Bearing capacity efficiency” (BCE), “Failure load ratio” (FLR), “Vertical stress ratio (VSR) and “Contact pressure ratio” (CPR). BCR is the ratio of bearing capacity of skirted strip footing to that of an equivalent plane footing having same length and contact area and placed at the top level of a skirted footing. BCE is the ratio of bearing capacity of skirted strip footing at the interface to that of equivalent plane footing. FLR is the ratio of experimental failure load to the theoretical failure load for a given model. VSR at a given depth coefficient z/B1 and width coefficient x/B1 is the ratio of the vertical stress, σw at that point to the applied pressure q. CPR is the ratio of contact pressures at a given location of a skirted footing to that of a plane footing having width equal to the projected width of skirted footing. The general inferences derived from the investigation are:

1. The failure load of skirted footings is independent of the roughness of footing base because of the frictional contact surface of confined sand mass within the skirts with foundation sand mass, unlike the behaviour of conventional footing, wherein direct contact of footing with sand is prevailing.

2. The failure load seems to vary non-linearly with the width of conventional footings and projected width of skirted footings unlike Terzaghi’s theory. This is because the average shear strength along the slip line under the foundation varies inversely with footing size.
The increase in the modulus of elasticity of confined sand mass as found from experimental observations of destiny measurements and triaxial tests and further verified by finite element analysis depends on the angle of skirt $\alpha$ and is maximum in the range of $\alpha = 30^\circ$ to $45^\circ$.

The main findings inferred from this work with respect to axi and non-axisymmetric loading using new parameters and plots are:

**AXIAL LOADING**

(1) Although the pattern of load-deformation curves remain similar to that of conventional footings, bearing capacity ratio and bearing capacity efficiency for given top width and width of the skirt increases up to the angle of skirt of $30^\circ$, beyond which it drops confirming to the modified theory of present work. The similar is the observation with skirted footings subjected to various surcharge loads exhibiting proportionate increase in bearing capacity. It is attributed to the quantum of confined sand mass within the skirts. For given top width $B_t$ and angle of skirts $\alpha$, the failure load increases with the width of the skirts.

(2) Though the settlement at failure load seems to be more in skirted footings, the measured load at the same settlement is quite high in skirted footings as compared to the conventional one.

(3) The contact pressure distribution under the conventional footings is observed to be parabolic shaped having zero values at the edges and maximum value at center whereas for the skirted footing it is nearly uniform throughout the width having little higher values at the center. In case of skirted footing with surcharge, the effect of skirt is to help making the contact pressure diagram more uniform which is predominant with $\alpha = 30^\circ$.

(5) In case of conventional footing, the contact pressure distribution at one third failure load is bowl shaped showing zero pressure at edges. At two third the failure load the magnitude of contact pressure at center increases. This trend continues up to the failure load. In case of skirted footings, at one-third failure loads, the pressure at the edges is much larger than at the center, which increases faster with the load. At two-third-failure load, the central value is more than the edge values and at failure load a nearly uniform contact pressure distribution is obtained with little larger value at the centre. This trend is observed in prototype testing also. It seems that the lower value of factor of safety may be adopted for determining the allowable bearing pressure due to this advantageous observation.
(6) The contact pressure ratio (CPR) at centre increases linearly up to $2/3$-rd failure load and it may tend to constant. Also at all percentages of failure loads, the CPR increases with the skirt angle up to $\alpha = 30^\circ$, beyond which it decreases. At junction point contact pressure ratio increases with the loads.

(7) The radius of the pressure bulb increases with the increase of skirt angle in the range of $30^\circ$ to $45^\circ$, beyond which it decreases. The radius of the pressure bulb for any fraction of the applied stress is more compared to the conventional footing. Also for the given vertical stress ratio the depth coefficient $z/B_1$ is more compared to the conventional footing which indicates that the significant depth for settlement computation or shear failure calculation is more in comparison to the conventional one for the given value of $\alpha$. However, if a plate deriving the same vertical load as the skirted footing is used, the actual extent of the pressure bulb for plane footing will be more than that of the skirted footings. Moreover, the concept of equivalent plane footing also justify the statement thereby skirted footing derives more advantage of low interference of pressure bulb with adjacent footing and significant depth.

(8) For a given depth coefficient ($z/B$), the vertical stress ratio is less compared to the conventional footing which indicates that the significant depth for settlement computation or for shear calculations is 30 to 40% less in skirted footings compared to that of conventional one.

**ECCENTRIC LOADING**

(1) For the same skirt angle, top width and width of skirt, the failure load decreases with increase of eccentricity. For same $e/B_t$ ratio the failure load, $BCR_{sfs}$, $BCE_{sfs}$, $BCR_{wp}$ and $WD$ increase up to $\alpha = 30^\circ$ to $45^\circ$ and thereafter reduces. Also for the same $e/B_t$ ratio, above parameters increase linearly with aspect ratio.

(2) In case of skirted foundation, the state of confined stress within the skirt attribute to resist more failure load compared to the conventional footing for the same eccentricity. Also, the skirted footing having $B_t = 300$ mm, $k = 0.33$, angle of skirt of $30^\circ$ resists 1.8 times the failure load compared to the conventional footing while the $45^\circ$ skirt exhibits 1.5 times the failure load.

(3) It seems that the skirted footing can be subjected to larger eccentricity than that of conventional footing without loosing its contact with sand. Also, skirted footing can resist a larger load at a given eccentricity than the conventional footing. The same behaviour is observed for the given settlement, say 2.5%, 5%, and 7.5%, of the projected width of skirted footing.
(4) The contact pressure distribution diagram for skirted foundation reveals that the
tendency towards negative contact pressure —within the limits of eccentricity
\(e<0.5B_1\) is reduced to a greater extent compared to the conventional strip
footings. Similar is the observation with the eccentric and oblique loads. This is
because of the interlocked stresses in the confined sand mass in the inert zone
on the other side of the load application.

(5) The characteristics of the pressure bulb illustrate unsymmetrical pattern, which is
stretched on the eccentric load side. Among various eccentric loading, radius of
pressure bulb on the load side at any depth coefficient is increased with
increase of eccentricity. This profile is pronounced at higher depth coefficient.

(6) The angle of tilt at failure load and at a given settlement is less in skirted footing
compared to that of conventional one. The ratio of contact pressure on load
side to that of the remote side reduces with angle of skirt up to 30° and then
increases at all loads.

(7) The experimental modulus \(E_s\) increases with low eccentricity thereafter varies
inversely with higher eccentricity of the applied load. The experimental modulus
is the secant modulus as obtained from pressure settlement diagram at a
specified load.

**OBLIQUE LOADING :**

(1) For same skirt angle, top width and width of skirts, the failure load per unit length
BCR and BCE of footing decreases with increase in eccentricity and inclination
of load.

(2) Amongst two skirt angles 30° and 45°, with the increase of skirt angle (i.e. \(\alpha =
45°\), the failure load decreases for the same inclination and eccentricity.

(3) The failure load resisted by skirted footing is considerably high as compared to
the conventional footing for the same \(e_x/B\) ratio and inclination of the load.

(4) For the same settlement, the skirted footing having angle of skirt 30° resists
about 1.8 times the failure load as compared to conventional footings while that
with skirt angle of 45°, exhibits about 1.65 times the failure load.

(4) It is found that the skirted footing can resist large eccentric oblique loads than
the conventional footings without loosing its contact with sand. Also for a given
load, this footing can resist more obliquity and simultaneously more eccentricity.
For any obliquity the failure load increases from \(\alpha=0°\) to 30° thereafter it drops.
The profile of a contact pressure distribution diagram is dependent on the direction of the horizontal component of incident load along the interface of confined sand mass and the foundation sand mass for a given eccentricity.

The contact pressure distribution diagram for skirted footing subjected to eccentric and eccentric oblique loads reveal that the tendency towards negative contact pressure is increased in case of oblique load. Also, this tendency varies with angle of inclination.

The profile of the pressure bulb indicates non-uniform pattern. This unsymmetrical characteristic is dependent on the position of point of incidence of oblique load at plane of interface between confined sand mass within skirt and foundation sand mass.

Among various inclinations of loads, the size of respective pressure bulb at any depth - coefficient is increased with the increase of angle of inclined load in the direction of its horizontal component.

HORIZONTAL LOADING

The load displacement (sliding) patterns are similar to that of vertical loads. The failure load increases with angle of skirt and depth of skirt (aspect ratio). It will be maximum at angle of skirt of 90°.

At all percentage of failure load, the horizontal resistance offered in skirted foundation is found to be pronounced than the calculated theoretical load based on resistance against sliding. This resistance is contributed by modified value of the frictional angle as suggested in the theoretical development and passive resistance developed adjacent to the skirt. Percentage contribution of passive pressure in offering total resistance increases with angle of skirt up to 90°.

The theoretical curves for bearing capacity factors based on proposed analytical model are seen to agree adequately in experimental observations. The FEM analysis employing ANSYS software suggests that the equivalent modulus of sand within the skirts increases up to an angle of skirt of 30° which drops thereafter, reaches to more or less same value of plane footing at an angle of skirt of 90°.

Looking at the above findings it seems that the skirted footings can be advantageously adopted in practice for numerous applications. The computer programme included in this work can help to facilitate the field engineer for determining the bearing capacity parameters for the use in design.